Factors Affecting the Differential Capture of Male and Female Codling Moth (Lepidoptera: Tortricidae) in Traps Baited with Ethyl (*E*, *Z*)-2,4-Decadienoate

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ABSTRACT Studies were conducted in apple to evaluate factors that differentially affect the catch of male and female codling moth, *Cydia pomonella* L., in traps baited with ethyl (*E*, *Z*)-2,4-decadienoate (pear ester). We examined the time of moth capture in the diel cycle and the recapture rates of marked moths in sex pheromone mating disruption (MD) and untreated orchards. The attractiveness of pear ester–baited traps was compared among five apple cultivars. Experiments also assessed the influence of trap height, the distance of the trap from sex pheromone dispensers, proximity of foliage surrounding the trap, trap size, and proximity of adjacent clean and codling moth–injured fruit on moth captures. The responses of male and female moths significantly differed in response to many of these factors. For example, the time of peak female capture occurred earlier than for males. A higher proportion of recaptured, marked moths were females in MD versus untreated orchard plots. Significantly more male but not female moths were caught in traps placed high versus low in the tree canopy. Traps placed on the perimeter of the canopy caught significantly more female moths than traps placed within the canopy and surrounded by foliage. Smaller trap surfaces caught significantly more males than females. Traps placed adjacent to uninjured fruit caught significantly more females than traps placed away from fruit. No differences occurred between sexes in response to other factors: significantly higher counts of both sexes occurred in blocks of 'Granny Smith' versus four other apple cultivars; recapture rates of marked moths were not different at release points ranging from 10 to 50 m for either sex; and trap placement relative to MD dispensers or injured versus uninjured fruits was not a significant factor affecting moth catches or their sex ratio. Effective monitoring for either or both sexes of codling moth should consider standardizing these factors. Lure and kill strategies should include factors that optimize the captures of female moths.

KEY WORDS *Cydia pomonella*, kairomone, monitoring, pear ester

THE PEAR ESTER, ethyl (*E*, *Z*)-2,4-decadienoate, has been identified as a kairomone for both sexes of codling moth, *Cydia pomonella* L. (Light et al. 2001). Season-long field studies conducted in different host crops and cultivars have shown that pear ester–baited traps can catch similar or greater numbers of moths than sex pheromone–baited traps in orchards treated with sex pheromone mating disruption (MD) (Light et al. 2001, Thwaite et al. 2004, Knight et al. 2005a). In addition, the sex ratio of moths caught in pear ester–baited traps tracks the differential emergence (protandry) of codling moth's sexes during the season (Light et al. 2001). The attractiveness of pear ester for female codling moth is particularly important and allows pest managers to better track population densities and timing of oviposition and egg hatch (Knight et al. 2002a).

The proportions of female codling moth caught in pear ester–baited traps have varied widely in different studies. Light et al. (2001) evaluated a pear ester lure in walnut, apple, and pear orchards treated with and without MD. Initially the pear ester lure caught more males than females in all orchards, but later in the season, traps caught a higher proportion of females, except in pear and apple orchards not treated with MD. Similar patterns of moth catch were found in apple (Knight and Light 2005) and pear (Knight et al. 2005a) orchards treated with MD and in untreated apple orchards (Ioriatti et al. 2003). Surprisingly, Il'ichev (2004) caught only 5.0 and 10.0% females in pear and apple orchards treated with and without MD, respectively, throughout the entire season in Australian orchards. Differences in the sex ratio of captured moths have been found with lures loaded from 0.1 to 40.0 mg (Knight and Light 2005). A gray halobutyl

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elastomer septum loaded with 3.0 mg was the most effective lure for monitoring female codling moth and caught a significantly higher proportion of virgin females than lures loaded at other rates (Knight and Light 2005). Identification of other factors affecting the capture of female codling moths has not been reported.

Understanding the response of male and female codling moth to pear ester–baited traps is a prerequisite in developing an effective kairomone-based monitoring program. Codling moth's antennae possess specific receptor cell neurons that respond only to pear ester and other cells that respond to both codlemone and pear ester (De Cristofaro et al. 2004). No differences were found in the EAG olfactory responses of moths collected from apple, pear, or walnut orchards; the mating status of either sex was not a significant factor affecting antennal response (De Cristofaro et al. 2002). The magnitude of male and female antennal electroantennogram response to pear ester was similar in one study (De Cristofaro et al. 2004), but males were more responsive than females in another study (Avilla et al. 2003). Exposure to high levels of codlemone reduced the antennal response to pear ester of both sexes (De Cristofaro et al. 2004). In field-trapping studies, the addition of pear ester to high rates of codlemone reduced male but not female captures, whereas adding a high rate of pear ester to codlemone reduced captures of females but not of males (Knight et al. 2005b).

Male and female adult codling moth response to pear ester in laboratory flight tunnels has been weak. Sauphanor et al. (2002) was not able to elicit a flight response of female moths to a pear ester lure in their flight tunnel. Less than 20.0% of female codling moths were caught in a pear ester–baited trap placed in a flight tunnel after 16 h in continuous darkness (A.L.K., unpublished data). Ansebo et al. (2004) had only 3.0% of male moths initiate flight in their tests with the pear ester, and no upwind orientation was observed except when the pear ester was combined with (E, E)-α-farnesene and (E)-β-farnesene. Reed and Landolt (2002) observed upwind flight with female codling moths in a flight tunnel to volatiles emitted by apple fruits and especially from injured fruits. Similarly, female response to pear ester was significantly increased when detached apple fruit and foliage were added to a flight tunnel (A.L.K., unpublished data).

Light et al. (2001) hypothesized that the low captures of codling moth in traps baited with pear ester in pear orchards was caused by competing volatiles. However, Knight et al. (2005a) found that pear ester was an effective lure for male and female codling moth in pear orchards except in 'Bartlett' orchards with fruit injury. A population model developed to compare the effectiveness of a male-only versus a bisexual attracticide showed that fruit load could have a significant effect on the performance of mass trapping with pear ester–baited traps (Knight et al. 2002a). However, the competitive or additive effect of surrounding foliage, fruit load, and injured fruits on trapping efficiency has not been studied.

Herein we report a series of codling moth trapping studies using pear ester in apple orchards. Our objectives were to determine the time of moth capture within the diel cycle; the performance of traps in both untreated and MD-treated blocks and within orchards of five major apple cultivars treated with MD; and the influence of trap height, size, distance from sex pheromone dispensers, proximity to foliage, and proximity to adjacent clean and codling moth–injured fruit on moth captures. These data are important in standardizing the use of pear ester lures and improving the trapping of female moths for lure and kill strategies.

Materials and Methods

Moth Captures over the Diel Cycle. The temporal pattern of male and female moth catch in traps baited with pear ester was evaluated in a 20.0-ha 'Delicious' apple orchard on 11–12 June 2000. The orchard was planted on a 4 by 6-m spacing and tree heights ranged from 4.0 to 4.2 m. The orchard was treated with 1,000 Isomate-C PLUS dispensers (Pacific Biocontrol, Vancouver, WA) per hectare. Dispensers loaded with 182.3 mg of a 60:33:7 blend of (E,E)-8–10-dodecadien-1-ol, dodecanol, and tetradecanol were attached to branches in the upper third of the orchard's canopy. Eleven diamond-shaped traps (Pherocon IIB; Trécé, Adair, OK) baited with a 3.0-mg lure (Pherocon CM DA; Trécé) were placed in the orchard at 0800 hours on 11 June. Traps were placed on poles at 3.0 m in the canopy and spaced 75 m apart. Moths were removed from all traps at 1600, 1800, 2000, 2200, 2400, and 0800 hours ($\pm$15 min) on both days. Female moths were dissected to determine their mating status.

Effect of Sex Pheromone MD on Moth Catch. Four orchard blocks (2.0 ha) were established within a 25.0-ha apple orchard of mixed cultivars situated near Moxee, WA, in 2000. Blocks were separated by 100 m of untreated orchard. Two blocks were treated with 1,000 Isomate-C PLUS dispensers per hectare, and two blocks were left untreated. A delta-shaped trap (Pherocon VI; Trécé) baited with a 50.0-mg pear ester lure was placed in the center tree of each of the four blocks. Traps were attached to poles and placed in the upper third of the canopy. Trees were marked in the four cardinal directions from this trap at distances of 10.0, 20.0, 30.0, and 50.0 m. Sterile codling moths of both sexes were obtained from the codling moth mass-rearing SIR facility in Osoyoos, British Columbia. Moths were sterilized with gamma radiation (33 krad) from a Cobalt^{60} source (dose rate of 1,150–1,320 rad/min) and held at 0–2°C before field release. Moths (2–3 d old) were placed in closed cardboard containers coated with a small amount of fluorescent powder (DayGlo Color, Cleveland, OH). Three hundred unsexed, sterile moths were released from each of the 16 positions around each trap by attaching a container with chilled moths to the trunk of the marked tree at a height of 2.0 m. A different color powder was used for each of the four distances. Traps were checked after 7 d, and moths were sexed and examined under UV illumination (Black-Ray Long Wave UV Lamp, Ultra-Violet Products, San Gabriel, CA) to determine the presence and color of any mark. The study was repeated on three dates: 21 and 28 July and 4 August.

Influence of Cultivar. Studies were conducted in 50 apple orchards (8–16 ha) situated near Brewster, WA, during 2001. Ten orchards of five cultivars were selected, including 'Granny Smith', 'Fuji', 'Delicious', 'Golden Delicious', and 'Gala'. Orchards were typically interplanted with a second cultivar or crabapple as pollenizers, and these constituted <20% of the acreage within each orchard. All orchards were treated with Isomate-C PLUS dispensers applied at rates of 500–1,000 dispensers per hectare. All orchards were monitored with four delta-shaped traps baited with two replicates of either sex pheromone (Megalure) or pear ester (Pherocon CM DA) lures (Trécé). Traps were spaced 100 m apart. Moths were sexed, counted, and removed from traps each week from 9 May to 15 September. Sticky trap liners were replaced when >20 cumulative moths were caught. Fruit injury was assessed in early September by visually inspecting 30 fruits from 20 randomly selected trees situated <50 m from each trap.

Effect of Trap Size on Moth Catch. Two experiments were conducted in the same 20.0-ha 'Delicious' orchard to examine the influence of trap size on the capture of male and female codling moth with a pear ester lure during 2000. In the first experiment, traps were constructed by cutting Pherocon 1CP sticky trap liners (Trécé) into different sized squares. Five incrementally (2.5 cm) larger trap sizes were prepared from 5.0 by 5.0 cm to 15.0 by 15.0 cm. A 44.0-mg drop of black paste baited with 1.0% pear ester by weight (Trécé) was placed in the center of each card. Ten replicates of each trap size were placed in the orchard in a completely randomized design on 25 August. Traps were spaced 20 m apart and attached horizontally in the canopy with pins at a height of 2.0 m. Moths were removed from cards on 29 August and 1 and 15 September. All moths were removed and sexed, and their distance on the card from the lure drop was measured.

In a second experiment, a 1-m^2 piece of cardboard was covered with a thin coating of adhesive (Tangle-trap; Gemplers, Janesville, WI) and baited with a 3.0-mg pear ester septum placed in the center of the trap. The trap was placed in the center of an apple tree canopy at a height of 2.0 m on 10 September 2000. All moths collected after five nights were sexed, and their distance to the lure was measured.

Effect of Trap Placement Within the Canopy on Moth Catch. The influence of placing diamond-shaped traps baited with a 3.0-mg pear ester lure adjacent to an Isomate-C PLUS dispenser was evaluated in a 'Delicious' orchard treated with 1,000 Isomate-C PLUS dispensers per hectare in 2001. Ten traps were placed either <15.0 cm and >1.0 m from dispensers on individual trees. Traps were spaced >30 m apart, and treatments were randomized within the orchard. Traps were placed in the orchard on 9 September and checked on 20 September.

The effect of trap height within the canopy was evaluated in the same orchard during 2001 on eight dates from 24 July to 6 September. On each date, five diamond-shaped traps baited with a 3.0-mg pear ester lure were each placed randomly in the orchard at a height of either 2.0 or 3.0 m. The mean height of the trees was 4.2 m. Traps were spaced 30.0 m apart and were checked after 5–7 d.

The influence of surrounding foliage on moth catch in traps baited with pear ester was evaluated in four orchards. All orchards were mature plantings of 'Delicious' on either a 5.0 by 6.0-m or 4.0 by 6.0-m planting density. The mean canopy height in the mature orchards ranged from 4.0 to 4.2 m. All orchards were treated with 1,000 Isomate-C PLUS dispensers per hectare. Delta-shaped traps were placed in the orchard's canopies using two methods. One-half of the traps were placed within the canopy by attaching the trap's metal wire to a branch. These traps were closely surrounded by foliage; however, their openings were not blocked. The other traps were attached to a pole that was hung from a branch in the tree and positioned on the perimeter of the canopy. These traps had little adjacent foliage within 0.5 m of their openings. All traps were placed 1.0 m from the top of the canopy. On each date, 5–10 replicates of each trap position was randomized within an orchard. Studies were conducted on 20 August and 25 September 2000 and 25 May 2001. Traps were baited with a 3.0-mg septum loaded with pear ester, and traps were checked after 5–7 d.

Effect of Adjacent Fruit on Moth Catch. The influence of adjacent injured or uninjured fruit or no fruit on male and female catches in a pear ester–baited trap was evaluated in 2000. The study was conducted in a 'Fuji' orchard with >30% fruit injury. The orchard was planted with a 5.0 by 3.0-m tree spacing, and mean canopy height was 2.8 m. Sixty trapping sites were arbitrarily selected within the orchard on 2 August that were characterized by either having adjacent fruit clusters with no injury, fruit clusters with most of the fruit injured by codling moth, or no fruit within 1.0 m. Diamond-shaped traps with a 3.0-mg pear ester lure were placed in each site. Sites were separated by >20.0 m within the orchard. Sterile, unsexed codling moths (4,000) were released into the orchard on 3 August by tapping chilled moths from petri plates along transect lines spaced 10.0 m apart throughout the orchard. Traps were checked after 7 d.

Statistical Analyses. Analysis of variance (ANOVA) was used to compare treatment effects on moth counts and percentages of females and mated females (Analytical Software 2000). All moth count data were square-root transformed and all percentages were arcsine-square-root transformed before analyses. Only untransformed data are reported. When a significant treatment effect was observed ($P < 0.05$), means were separated using Fishers least significant difference (LSD) test. The temporal pattern of moth catch was analyzed as a one-way ANOVA. The influence of sex pheromone MD on the recapture of marked moths released at four distances was analyzed as a three-way

Table 1. Diel captures of male and female codling moth in traps baited with pear ester on 11–12 June 2000

Time period (hours)[a]	Mean ± SE moth catch per trap			Mean ± SE proportion	
	Male	Female	Total	Female moths	Mated females
1600–1800	0.0 ± 0.0a	0.1 ± 0.1a	0.1 ± 0.1a	1.00 ± 0.00	1.00 ± 0.00
1800–2000	0.6 ± 0.2b	1.0 ± 0.2b	1.6 ± 0.3b	0.57 ± 0.10	0.36 ± 0.12
2000–2200	1.7 ± 0.3c	1.0 ± 0.3b	2.8 ± 0.5c	0.35 ± 0.07	0.20 ± 0.10
2200–2400	0.5 ± 0.3ab	0.2 ± 0.1a	0.7 ± 0.4ab	0.19 ± 0.14	0.17 ± 0.17
0000–0800	0.3 ± 0.2ab	0.2 ± 0.1a	0.5 ± 0.2a	0.47 ± 0.18	0.25 ± 0.25
ANOVA df = 4, 105	$F = 8.97$	$F = 8.31$	$F = 11.00$	$F = 2.09$[b]	$F = 1.04$[c]
	$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P = 0.10$	$P = 0.41$

Column means followed by a different letter are significantly different, LSD test, $P < 0.05$.
$n = 11$.
[a] Sunset occurred at 2150 hours.
[b] Degrees of freedom in the ANOVA were 4,43.
[c] Degrees of freedom in the ANOVA were 4,27.

ANOVA, with treatment, date, and distance as factors. The influence of apple cultivar on moth catch in sex pheromone and pear ester–baited traps and the percentage fruit injury across cultivars were analyzed separately with one-way ANOVAs. The total number of moths and the proportion of female moths among traps of different sizes were analyzed with one-way ANOVAs. The mean distance between male and female moths from a lure on traps was compared using a paired *t*-test. The effect of placing traps near or far from sex pheromone dispensers was analyzed with a one-way ANOVA. The effect of trap height and surrounding foliage were analyzed as randomized complete block ANOVAs with date and orchard as the blocking variables, respectively. The influence of fruit injury adjacent to traps was analyzed with a one-way ANOVA.

Results

Moth Captures over the Diel Cycle. Significant differences in male, female, and total moth catch occurred among the five time periods (Table 1). Male and total moth catch from 2000 to 2200 hours were significantly higher than at all other time periods. In addition, total moth catch during 1800–2000 hours was significantly higher than at either 1600–1800 or 0000–0800 hours. Female moth catch was significantly higher from 1800 to 2200 hours than during the other three time periods. No significant difference occurred among time periods for the proportion of females and the proportion of mated females caught in traps (Table 1).

Effect of Sex Pheromone MD on Moth Catch. Less than 1% of the marked, sterilized moths were recaptured in traps baited with pear ester in either treatment (Table 2). The effect of distance that moths were released from a pear ester–baited trap in both untreated and sex pheromone MD plots was not a significant factor affecting the recapture of male, female, or total moths ($P > 0.85$). The interaction of distance with date and treatment and the three-way interaction were also not significant in any of the ANOVAs ($P > 0.70$). Significant differences in the catch of females ($F = 25.37$; df = 2,24; $P < 0.0001$) and total moths ($F = 6.06$; df = 2,24; $P < 0.01$) occurred among the three test dates. The sex pheromone MD treatment was a significant factor affecting male and total moth catch, with lower mean catch in the sex pheromone MD than untreated plots (Table 2). The interactions of treatment and date were not significant in any ANOVA ($P > 0.05$). The distance where moths were released from traps was not a significant factor affecting the proportion of captured moths that were females ($P = 0.21$) nor were the interactions of distance with treatment or date or the three-way interaction significant ($P > 0.15$). Date, however, was a significant factor affecting the proportion of female moths recaptured ($F = 5.59$; df = 2,15; $P < 0.05$).

Influence of Cultivar. Cultivar was a significant factor influencing catches of male and female codling moth in traps baited with pear ester (Table 3). Total moth catches were 6 to 14 times higher in 'Granny Smith' than the other four cultivars. The proportion of female moths caught in pear ester–baited traps did not vary among cultivars ($F = 0.51$; df = 4,39; $P = 0.73$) and ranged from 0.29 to 0.44. Similarly, the proportion of trapped females that were mated did not vary among cultivars ($F = 0.72$; df = 4,39; $P = 0.59$) and ranged from 0.74 to 0.93. In comparison, male catches in sex

Table 2. Influence of sex pheromone MD on recapture of marked codling moth adults in traps baited with pear ester

Treatment[a]	Mean ± SE moth recapture from each release distance per trap[c]			Mean ± SE proportion females moths
	Male	Female	Total	
MD	0.6 ± 0.2	2.2 ± 0.5	2.8 ± 0.5	0.74 ± 0.07
No MD	3.0 ± 0.7	1.8 ± 0.3	4.8 ± 0.8	0.43 ± 0.06
ANOVA[b]	$F = 9.40$	$F = 0.87$	$F = 4.31$	$F = 12.20$
	$P < 0.01$	$P = 0.36$	$P < 0.05$	$P < 0.01$

[a] Treatments were replicated in two 2.0-ha blocks separated by 100 m. Studies were initiated on three dates: 12 and 28 July and 4 Aug. and ran for 7 nights.
[b] This study was analyzed as a three-way ANOVA with treatment, date, and distance as factors. Degrees of freedom in the three-way ANOVA for treatment was 1,24 except for the proportion of females which was 1,15 because of the exclusion of data when no moths were caught.
[c] Three hundred unsexed moths were released at 10, 20, 30, and 50 m at the four cardinal positions from each trap.

Table 3. Mean moth catches in traps baited with a sex pheromone or pear ester lure and surrounding fruit injury in apple orchards of different cultivars treated with sex pheromone MD, 2001

Apple cultivar	Mean ± SE moth catch per trap[a]				Mean ± SE percent fruit injury surrounding traps[b]	
	Sex pheromone–baited	Pear ester–baited				
	Total	Male	Female	Total	Sex pheromone	Pear ester
Gala	4.9 ± 2.4	2.6 ± 0.8a	1.3 ± 0.5a	3.9 ± 1.3a	0.09 ± 0.05	0.12 ± 0.10
Golden Delicious	1.4 ± 0.8	1.9 ± 0.9a	2.8 ± 1.7a	4.7 ± 2.3a	0.23 ± 0.22	0.34 ± 0.27
Delicious	5.9 ± 2.2	6.7 ± 2.2a	2.6 ± 0.9a	9.3 ± 3.3a	0.24 ± 0.12	0.13 ± 0.11
Fuji	1.8 ± 0.8	2.9 ± 0.8a	1.5 ± 0.5a	4.3 ± 1.3a	0.09 ± 0.08	0.13 ± 0.12
Granny Smith	3.7 ± 1.8	27.6 ± 9.2b	25.5 ± 9.6b	55.5 ± 9.6b	0.49 ± 0.19	0.48 ± 0.22
ANOVA df = 4, 45	$F = 1.18$	$F = 13.10$	$F = 5.67$	$F = 7.87$	$F = 1.27$	$F = 1.19$
	$P = 0.33$	$P < 0.0001$	$P < 0.001$	$P < 0.001$	$P = 0.30$	$P = 0.33$

Column means followed by a different letter were significantly different, $P < 0.05$, LSD test.

[a] Delta-shaped traps were baited with either the high-dose sex pheromone lure, Pherocon CM Megalure, or the pear ester lure, Pherocon CM DA (Trécé).

[b] Thirty fruits from 20 trees at a distance of <50 m from the traps were visually inspected for codling moth injury.

pheromone–baited traps did not differ among cultivars (Table 3). The percent fruit injury surrounding both the pear ester– and sex pheromone–baited traps averaged <0.5% and did not differ among cultivars (Table 3).

Effect of Trap Size on Moth Catch. No significant differences were found in the mean distance of male versus female moths from a lure placed on traps of various sizes (Table 4). However, trap size affected the mean total number of moths caught. Significantly, more females and total moths were caught on the three larger traps (>161.3 cm^2) versus the three smaller traps. Significantly more males were caught on the four largest traps (>104.0 cm^2) versus the smallest two traps (Table 4). The proportion of female moths was significantly higher on the three largest traps versus the three smallest traps. No female moths were caught on the smallest card.

Cohorts of male and female moths were caught at a similar mean distance from a pear ester lure placed in the center of a 1-m^2 trap (23.1 ± 4.1 versus 21.1 ± 0.7 [SE] cm; $t = -0.46$, df = 12.8 [unequal variances], $P = 0.65$). The proportion of female moths caught on this trap was 0.35. Female moths were only caught at distances >15.0 cm from the lure compared with 30% of the males caught at distances <15.0 cm.

Effect of Trap Placement Within the Canopy on Moth Catch. No difference was found in the catch of both sexes and total moths in pear ester–baited traps placed adjacent to (<15.0 cm) or 1.0 m from Isomate-C PLUS dispensers ($t < 0.20$; df = 18; $P > 0.85$). Trap height within the canopy was a significant factor affecting male and total moth catches with higher counts occurring in traps placed at 3.0 versus 2.0 m (Table 5). Trap height did not significantly affect the catch of female moths in pear ester–baited traps. Placing traps within the canopy and surrounded by foliage versus on the perimeter and free from foliage significantly increased the capture of females but not males or total numbers of moths (Table 6). The proportion of female moths caught was not significantly different in traps placed in either position.

Effect of Adjacent Fruit on Moth Catch. No significant difference in moth catch occurred in the number of males and total number of moths caught in traps adjacent to uninjured, injured, or no fruits (Table 7). However, significantly more females were caught in traps adjacent to uninjured fruits compared with no fruits. No difference was found in the catch of female moths in traps adjacent to either clean versus injured fruits. The proportion of female moths caught did not differ significantly among these three trap positions.

Table 4. The mean distance of male and female codling moth from a pear ester lure and the proportion of female moths caught on horizontal sticky traps of various sizes

Trap size (cm^2)[a]	Mean ± SE distance between moth and lure[b]		Mean ± SE moths per trap			Mean ± SE proportion female moths
	Male	Female	Male	Female	Total	
26.0	1.9 ± 0.1	—	0.5 ± 0.2a	0.0 ± 0.0a	0.5 ± 0.2a	0.00 ± 0.00a
57.8	3.1 ± 0.1	2.9 ± 0.3	0.6 ± 0.3a	0.2 ± 0.1ab	0.8 ± 0.4a	0.19 ± 0.12ab
104.0	2.9 ± 0.2	2.8 ± 0.3	2.2 ± 0.4bc	0.8 ± 0.2b	3.0 ± 0.5b	0.25 ± 0.08b
161.3	3.9 ± 0.3	4.7 ± 0.2	2.2 ± 0.6b	2.5 ± 0.4c	4.7 ± 0.5c	0.56 ± 0.09c
231.0	5.3 ± 0.6	5.5 ± 0.4	2.6 ± 0.7bc	2.3 ± 0.3c	4.9 ± 0.8c	0.50 ± 0.08c
316.8	5.9 ± 0.4	6.4 ± 0.3	3.5 ± 0.5c	2.9 ± 0.4c	6.4 ± 0.6c	0.45 ± 0.04c
ANOVA df = 5, 54			$F = 9.38$	$F = 21.58$	$F = 29.87$	$F = 6.07$
			$P < 0.0001$	$P < 0.0001$	$P < 0.0001$	$P < 0.001$

Column means followed by a different letter were significantly different in a LSD test, $P < 0.05$.

[a] The maximum distances between the lure and the edge of the various-sized traps were 3.6, 5.4, 7.2, 9.0, 10.8, and 12.6 cm, respectively.

[b] No significant differences (paired t-tests, $P > 0.05$) were found between sexes in the mean distance from the lure of moths caught on each card size.

Table 5. Influence of trap height on catches of male and female codling moth in traps baited with pear ester placed in an apple orchard canopy with a mean height of 4.1 m

Trap height (m)	Mean ± SE moth catch per trap			Mean ± SE proportion female moths[a]
	Male	Female	Total	
2.0	0.6 ± 0.1	1.2 ± 0.3	1.8 ± 0.3	0.57 ± 0.08
3.0	1.4 ± 0.3	1.7 ± 0.3	3.2 ± 0.4	0.53 ± 0.07
ANOVA df = 1, 77	$F = 8.18$	$F = 2.30$	$F = 8.15$	$F = 0.22$
	$P < 0.01$	$P = 0.13$	$P < 0.01$	$P = 0.64$

[a] Degrees of freedom were 1,65 in the ANOVA with proportion of female moths because some traps did not catch any moths.

Discussion

Pear ester has proven to be a promising attractant for codling moth in apple orchards in diverse fruit growing regions including the United States, Australia, and Italy (Light et al. 2001, Ioriatti et al. 2003, Thwaite et al. 2004). In particular, the ability to capture female codling moths using this kairomone offers new opportunities to monitor this important pest. Studies reported here suggest that a variety of factors can influence the effectiveness of pear ester–baited traps to differentially capture each sex. For example, traps placed in MD versus untreated orchards catch fewer male moths, whereas traps placed high versus low in the canopy catch more males. In addition, traps placed on the perimeter of the canopy hanging free from surrounding foliage or placed adjacent to fruit catch more females than traps placed within the canopy surrounded by only foliage. Consideration of these factors could likely increase the precision of estimating the seasonal population densities of male and female moths and improve lure and kill strategies (Knight et al. 2002a).

The diurnal responses of male and female codling moth to pear ester–baited traps differed in our studies. Peak numbers of males were trapped during dusk, which is also the peak response time of males to sex pheromone–baited traps (Knight et al. 1994). Females were caught earlier than males, with the first moth caught before 1800 hours. This time period coincides with the peak timing of oviposition (Riedl and Loher 1980). Temperature can modulate these circadian rhythms, with low temperatures accelerating and high temperatures retarding the occurrence of sexual behaviors (Castrovillo and Cardé 1979, Riedl and Loher 1980). Similarly, unsexed moth counts in a pear ester–baited timing trap showed that moth catches did not occur during hours when temperatures were <11 and >23°C (A. L. K., unpublished data). However, unlike with sex pheromone–baited timing traps, where moth catch was restricted primarily to dusk and dawn, moths were caught in pear ester–baited traps throughout the scotophase and daylight hours. This greater plasticity of codling moth's response to pear ester than to sex pheromone may have significant effects on the relative moth catches during both moth flights with these attractants. For example, traps baited with pear ester may catch more moths than similar traps baited with sex pheromone early versus late in the season because of a more restricted occurrence of suitable temperatures for crepuscular moth flight in the spring versus summer months.

Table 6. Effect of trap position within the apple tree canopy on catches of male and female codling moth in traps baited with pear ester

Trap position[a]	Mean ± SE moth catch per trap			Mean ± SE proportion female moths
	Male	Female	Total	
Inside canopy	6.9 ± 1.2	2.9 ± 0.5	9.8 ± 1.3	0.32 ± 0.05
Canopy perimeter	7.7 ± 0.9	5.2 ± 0.8	12.9 ± 1.5	0.40 ± 0.02
ANOVA df = 1, 65	$F = 1.14$	$F = 12.71$	$F = 3.61$	$F = 2.73$
	$P = 0.29$	$P < 0.001$	$P = 0.06$	$P = 0.10$

[a] Traps were either attached to branches and placed inside the canopy surrounded by foliage or hung on poles on the outside perimeter of the canopy.

Table 7. Captures of codling moth (CM) adults in pear ester-baited traps placed adjacent to clean, CM-injured fruits, or no fruit

Trap placed adjacent to	Mean ± SE moth catch per trap			Mean ± SE proportion female moths[a]
	Male	Female	Total	
Uninjured fruits	1.6 ± 0.6	1.4 ± 0.4b	3.0 ± 0.9	0.60 ± 0.11
CM-injured fruits	2.4 ± 0.8	0.6 ± 0.1ab	3.0 ± 0.8	0.40 ± 0.10
No fruits	3.0 ± 0.9	0.4 ± 0.1a	3.4 ± 0.9	0.39 ± 0.13
ANOVA df = 2, 57	$F = 0.65$	$F = 3.29$	$F = 0.06$	$F = 1.01$
	$P = 0.53$	$P < 0.05$	$P = 0.94$	$P = 0.37$

Column means followed by a different letter are significantly different, LSD test, $P < 0.05$.

$n = 20$.

[a] Degrees of freedom were 2,41 in the ANOVA with proportion of female moths because some traps did not catch any moths.

The potential use of pear ester to monitor codling moth in pome fruits has been suggested to be greater in MD than untreated orchards because of its comparative higher catch relative to a sex pheromone lure in these former orchards (Light et al. 2001). However, we showed that male moth catch in traps baited with the pear ester lure is also significantly reduced in sex pheromone–treated orchards. It is not clear whether this reduction in male catch is caused by a competitive inhibition in response to pear ester (De Cristofaro et al. 2004) or altered male behavior in orchards treated with sex pheromone dispensers (Witzgall et al. 1999). The influence of varying dispenser density (250–1,000 dispensers/ha) or emission rate or the application of other sex pheromone–based control tactics, such as microencapsulated sprayables or widely spaced aerosol emitters (Knight 2000) on male and female attraction has not been examined. MD did not affect the recapture of female moths in our study, but the proportion of moths trapped that were female was significantly higher in MD than in the untreated orchard blocks. Similarly, a higher proportion of female than male moths were caught in pear ester–baited traps placed in MD versus untreated walnut orchards (Light et al. 2001). Thus, these data suggest that the numbers of female codling moth trapped with a pear ester lure could be used to establish female-based action thresholds in either type of orchard. However, the responses of sterilized codling moth adults under field conditions to several trap types have been shown to differ significantly from feral moths (Bloem et al. 1998); our data support findings that sterilized moths do not respond strongly to a pear ester lure (Thistlewood et al. 2004). Additional studies to develop female codling moth–based action thresholds should only be conducted with wild moths.

Traps baited with a pear ester lure were significantly more effective in capturing both sexes of codling moth in 'Granny Smith' than in the four other apple cultivars tested. Similarly, a pear ester lure outperformed several high-load sex pheromone lures over a 24-wk test in a block of 'Granny Smith' treated with MD (Thwaite et al. 2004). Significant differences in the attractiveness of a pear ester lure were also found among pear cultivars where a 3.0-mg pear ester lure outperformed sex pheromone lures in 'Comice' and 'D'Anjou' but not in 'Bosc' orchards (Knight et al. 2005a). These quantitative differences in the effectiveness of the pear ester lure among pome fruit cultivars may require that we establish cultivar-specific action thresholds for managing codling moth. Conversely, further studies should explore the addition of other host plant volatiles to pear ester, which might minimize differences among cultivars.

The significantly higher moth catches with pear ester in 'Granny Smith' versus other apple cultivars could be caused by either the presence (additive) or absence (competitive) of attractive odors characteristic of this cultivar. 'Granny Smith' is a distinctive green tart apple with a very long growing season (Warrington 1994). Fruit are typically harvested in early November in Washington State, whereas the second or partial third codling moth flight ends in mid-September (Beers et al. 1993). Apple cultivars exhibit a significant seasonal pattern of volatiles released from maturing fruit (Yahia et al. 1990, Hern and Dorn 2003). These odor profiles are characterized by a number of ester and terpenoid compounds that also elicit antennal response in codling moth (Bengtsson et al. 2001). Our hypothesis has been that the seasonal evolution of a suite of host volatiles characteristic of each crop and cultivar influence codling moth catches in pear ester–baited traps through competition (Light et al. 2001). 'Granny Smith' has a distinctive suite of aroma components that have been characterized at harvest (Lopez et al. 1998), but not during its growing season and during the time periods of codling moth adult activity. Comparisons of the odor profiles of 'Granny Smith' with other apple cultivars from May to September could be a useful qualitative approach to describe potential competitive interactions of pome fruit volatiles with a pear ester–baited trap (Light et al. 2001).

The active space of pear ester lures for male and female codling moths is unknown. However, our data with sterile moths found no difference in the recapture rates of either sex when moths were released 10–50 m from a pear ester–baited trap. These data are in contrast to similar recapture studies conducted with sterile, male codling moths by a sex pheromone–baited trap in either a MD or untreated orchard (A.L.K., unpublished data). Recapture rates in these studies fit a typical nonlinear response curve found in many mark–recapture studies with arthropods, natural $\log(\#\ \text{moths}) = a + b/\text{distance}$ (Taylor 1978). Collateral field studies with pear ester–baited traps have found that the maximum number of wild moths are caught per area when grids of traps are placed with a 15.0-m spacing, and significant reductions in fruit injury have extended only 15.0–30.0 m outside of orchard plots treated with insecticide-treated bait stations and surrounded by an untreated orchard (A.L.K., unpublished data). These data all suggest that pear ester–baited traps have a narrow active space. Current recommendations for the use of sex pheromone–baited traps for monitoring codling moth in MD orchards include the placement of one trap per hectare in a 100 by 100-m grid (Gut and Brunner 1996). Further studies are needed to assess the optimal density and arrangement of pear ester–baited traps to effectively monitor codling moth in commercial orchards.

Loading rate of pear ester into gray halobutyl septa has been found to be a significant factor affecting both total moth catches and the sex ratio of moths (Knight and Light 2005). In our studies reported here, we used three different lures: 3.0- and 50.0-mg septa and a 44.0-mg paste drop. However, these lures should have had similar levels of attractiveness. For example, moth catches of both sexes of codling moth with the two septa types have been reported to be similar, except early in the season when the higher loading is more attractive and strongly biased for males (Knight and Light 2005). The paste drop was formulated by Trécé to achieve similar moth captures in either delta- or diamond-shaped traps to the 3.0-mg septa but has not been used because of its much shorter residual activity (unpublished data). The 3.0-mg gray septa has become the standard lure because of its long life and consistent captures of female moths (Knight and Light 2005).

Significant differences were found in the capture of male and female codling moths based on trap size and placement within the canopy. Small trapping surfaces caught a higher proportion of males, and on very large trapping surfaces, female codling moths were caught only at distances >15.0 cm from the lure. The outside dimensions of the delta-shaped trap widely used to monitor codling moth in North America is 27 by 20 cm, with an opening of 8 by 16 cm, and the diamond-shaped trap used in some of our studies was smaller, but has a slightly larger opening (Knight et al. 2002b). No significant differences have been found in the effectiveness of either pear ester–baited trap in capturing both sexes of codling moth (unpublished data). Our data, however, suggest that captures of females may be enhanced if the trapping area was increased nearly four-fold. A pear ester–baited transparent vertical trap ($0.1\ m^2$) caught nine times more codling moth than the delta trap and may be a more useful design for potential lure and kill strategies (Knight 2005).

Trap height has been shown to be an important factor influencing codling moth male catch in sex pheromone–treated traps (Knight 1995a). Ioriatti et al. (2003) found that more moths were caught in pear ester–baited traps placed high versus low in the canopy, but surprisingly, they did not see a similar effect with sex pheromone–baited traps. Unfortunately, the influence of trap height on sex was not presented in this paper. Trap height only increased the capture of male and not female moths in our study. Close proximity of a pear ester–baited trap with a sex pheromone dispenser did not affect moth catch of either sex. This was in contrast to a previous study that showed that dispensers could influence male catch in sex pheromone–baited traps (Knight et al. 1999).

Significant effects caused by the placement of the trap within the canopy were also found because of the presence of foliage and fruit. The proximity of foliage with the trap reduced the captures of female but not male codling moths. This result may be related to the influence of trap size. We hypothesize that fewer female moths were caught in traps with surrounding foliage because of physical interference and the opportunity for females to land outside of the trap. Ioriatti et al. (2003) reported that a greater proportion of females than males landed outside of the trap when provided with a 30 by 30-cm panel situated below the trap. When traps are hung on the perimeter of the canopy and are distant from foliage, a greater proportion of females may land on and be captured in the trap. Thus, we hypothesize that increasing the trapping surface, reducing competing landing sites, and insuring a coherent plume structure should enhance female catch.

Apple fruit are known to attract codling moth females, and injured fruit are more attractive than uninjured fruit (Reed and Landolt 2002). In our studies, the catch of female moths was elevated when traps were deliberately placed next to fruit. This may have been caused by the additive influence of the fruit's volatiles and the pear ester lure. A similar effect was found in flight tunnel tests when (E, E)-α-farnesene and (E)-β-farnesene were added to pear ester (Ansebo et al. 2004) and in flight tunnel tests where detached apple shoots and uninjured fruit were placed adjacent to the pear ester–baited trap (A.L.K., unpublished data). Placing traps adjacent to injured versus uninjured fruit did not significantly affect female moth catch in our studies, although the mean catch was >50% lower with injured fruits. Reduced moth catches in pear ester–baited traps were found in 'Bartlett' pear orchards with significant levels of injured fruits but not within 'clean' orchards (Knight et al. 2005a). Optimal trap placement for monitoring female codling moth may consider avoiding border trees that typically have higher levels of injury (Knight 1995b) or cultivars within an interplanted block that are more susceptible to codling moth (Howell et al. 1992). Conversely, placing traps on 'Granny Smith' trees interplanted with other cultivars could elevate moth catches in pear ester–baited traps.

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